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LITERATURE REVIEW: TRACKING CONTROL MECHANISMS AND DISPLAYS (LIGHT ANTIAIRCRAFT SYSTEM ORIENTED)

Samuel A. Hicks

December 1957

Project No. TW-300

HUMAN ENGINEERING LABORATORIES

ABERDEEN PROVING GROUND,
MARYLAND

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ABSTRACT

A review of the literature dealing with tracking in general, control systems, display systems, compensatory vs. pursuit tracking, and auditory vs. visual displays. It is particularly relevant to designing fire-control systems for low-altitude antiaircraft weapons.

CONTENTS

LITERATURE REVIEW: TRACKING CONTROL MECHANISMS AND DISPLAYS (LIGHT ANTIAIRCRAFT SYSTEM ORIENTED)

INTRODUCTION

Antiaircraft tracking has become increasingly important with the advent of supersonic aircraft. While present antiaircraft systems may be quite capable of offering adequate protection against high flying aircraft, protection against low flying aircraft is a serious problem. This discrepancy may be accounted for by the difference in relative speeds of the two types of targets.

Until a system is developed that will automatically track a supersonic target through firing, the ultimate responsibility for tracking falls on the human operator. Therefore, the human element constitutes an important system parameter.

It is the intent of this paper to examine the various man-machine relationships by a review of the pertinent literature. No attempt is made to offer specific conclusions as to what system would be optimum for any particular set of conditions.

PURPOSE

The purpose of this report is to present some general background information pertinent to the design of tracking systems. The material presented herein is the result of a survey covering the available literature related to the tracking mechanisms and their components. This report will cover tracking in general, control systems, display systems, compensatory vs. pursuit tracking, and auditory vs. visual displays.

Tracking in General

There are four primary types of tracking systems:

a. Direct (position)

b. Rate (velocity)

c. Aided (rate-aided)

d. Regenerative

For the purpose of this paper, our concern is chiefly with aided or rate-aided and regenerative tracking since these are the types most generally used today. In order that a more comprehensive understanding of rate-aided and regenerative tracking may be gathered from this paper, a brief description of direct and rate tracking is warranted.

Direct tracking systems are those which require operator to position a reticle, cursor, etc., over a target by direct motion of his control. When this type of tracking system is used, the wide range of target velocities encountered in the tactical situation makes it necessary to compromise between coarse and fine control ratios. This results in a control that is too coarse for smooth tracking at low rates and too slow for accurate following at high rates.

Rate tracking systems are those in which the operator controls the rate of output of a variable speed mechanism installed to make tracking more accurate. Under this arrangement, the operator may turn the motor speed control to adjust the velocity and indirectly the position of the gun, or other aimed unit, until it matches the velocity and eventually the position of the target. While this allows the operator to follow high speed targets, hunting behavior results, for the operator is unable to correct a position error without introducing an erroneous rate. This erroneous rate causes overshooting unless the operator, through training and experience, has learned to anticipate the response of the control and reduces the corrective rate before the position error has been fully removed.

Rate-aided tracking is a combination of direct and rate tracking. In rate-aided tracking, a control adjustment by the operator changes both the position and rate of the tracking unit simultaneously. If the mechanism begins to lag the target, the target rate has increased and the operator manipulates the control to reset the mechanism on target, thereby simultaneously putting in a displacement correction and an increased rate which is proportional to the displacement of the control.

Fitts (13) in defining aided tracking used the following example:

> "If a watch had a single adjustment that would set the hands when the watch had lost a few minutes and also cause it to run faster thereafter, the adjustment would make use of the aiding principle."

In this example, a rate change has been made simultaneous with a position change. The ratio between rate change and position change is the aided tracking time constant and is expressed in seconds. The optimum time constant of a system is dependent upon the response of the operator to the rate of change of the error and the cumulative magnitude of the error before a corrective response is made.

$$\text{aided tracking time constant} = \frac{\text{change in position}}{\text{rate of change}}$$

Theoretically, after getting on target, this tracking system follows a constant velocity target without further adjustment. However, adjustments in azimuth, angular height, and slant range must be made continually due to changes in angular acceleration.

The tracking system that makes allowances for variations in target derivatives, and is capable of adjusting its output to match these variations continually with initial operator supervision and control, is a regenerative system.

Regenerative tracking is based upon the assumption that the target's behavior in the future bears a determinable relation to its behavior in the past. Should the aircraft deviate, i.e., change speed, etc., the component of its motion corresponding to the straight line projection will be supplied by the regenerative mechanism, leaving only the deviation to be supplied by the operator. An assumption of this type of system is that target course and velocity will remain constant for short periods of time, thus allowing the operator to be removed from the system for brief intervals such as during firing.

It has been suggested by Weiss (44) that the essential requirement for optimal operation of a regenerative system is that the operator be given no ambiguous duty to perform. He must, without exception, be called upon to supply the same response to the same stimulus.

In regenerative tracking a computer utilizes the known characteristics of the target to generate trial values of rate. Smooth tracking inputs must be supplied by the operator before the computer can regenerate the course. After receiving these inputs, the computer will continue to track as long as the target characteristics, i.e., course and velocity remain unchanged.

Control Systems

Essential to the optimal accuracy of any tracking device is the utilization of the proper type of control system. However, prior to the selection of a specific control, consideration must be given first to the task to be performed and, second, to the most efficient way to perform said task.

Since the tracking task is such a vital component of our air defense system, it is important to assure maximum effectiveness under all conditions. In this respect, it is not sufficient to merely provide for the average individual under normal conditions. Instead, it is in the stress situation that the need for a well-designed error-limiting control system becomes important. Fitts and Simon (12, 37) have reported that even when an individual greatly overlearns a response that is contrary to an earlier learned response he will, under the stress of an emergency situation, frequently revert to the earlier learned response. This phenomenon is defined as a reversal error. Fitts (14) referred to the earlier learned habit as a "population stereotype" or simply a preferred response, that is, that one of a number of alternative responses which are cultural in origin that is made by the greatest proportion of a population. Simon (37) investigated tracking performance using both preferred and nonpreferred response patterns. It was reported that stress resulted in more reversal errors for subjects utilizing nonpreferred responses than for those performing on a preferred one. In order that we may reduce these reversal errors, it has been suggested that control equipment be designed to utilize preferred responses.

The essential tasks in any tracking situation are detection, acquisition, and tracking. After acquisition, the operator is required to track the detected target through space. Azimuth, elevation, and range represent the dimensions by which an object may be located in space. Most present systems require the operator to track in azimuth and elevation while rather elaborate computer mechanisms supply the range information. The azimuth and elevation controls may be either one-dimensional dual controls or a single two-dimensional control.

The three most widely investigated types of controls are hand crank or hand-wheel, joy stick, and knob. In handwheel tracking, optimal performance is dependent upon a number of factors that may be built into the handwheel. They are size, speed, inertia, and friction. Since these four factors are interdependent, it would perhaps be better to consider them together rather than as separate entities.

The Foxboro Company, in a series of reports (9, 10, 11), covered these factors quite thoroughly. It was stated in one of these reports (11) that the effects of additional inertia, either in the form of a heavy handwheel or as a fly wheel, reduces tracking error materially. This reduction in error is a most significant one, varying between 40 percent and 50 percent depending upon the speed of tracking, the greatest reduction being at high speeds (50 to 200 rpm). With this inertial effect present, it is possible for the operator to hold a more constant speed of turning or to effect rate changes more smoothly in pursuit tracking courses.

While friction that is independent of the speed of control motion (coulomb friction) is undesirable, it must be realized that small amounts are unavoidable in mechanical systems. This friction often has an adverse effect on performance, particularly if it is large in relation to the mass stiffness and viscous friction (friction which is proportional to the rate of movement), in the system. This adverse effect usually results in performance decrement arising out of an increase in effective frictional torque. On the other hand, viscous friction has been found to be of definite advantage in many control systems. The beneficial results of this type of friction tend to minimize the effects of small fluctuations in force and to damp out high frequency oscillations, thus favoring maintenance of a steady output by the operator. Under conditions where jolting and vibration are present, the presence of this viscous friction, combined with the inertial effect mentioned above, enables the operator to track a smoother and more regular course.

The size of the handwheel seems to be of little importance when studied by itself. However, when this factor is combined with the optimum speed of rotation, it suddenly looms larger as a factor to be considered as a contributor to optimum tracking accuracy. Investigators have found that optimum handwheel size varies directly with the speed of rotation. The maximum speeds recommended for different sizes of handwheels varied from 140 to 200 rpm, with 200 rpm representing the human breakdown point -- that point at which the maximum effective speed of rotation is reached. In conjunction with this, the recommended handwheel radius varies from 2.25 to 4.50 inches. The smaller handwheel proves to be more effective at low speeds; at high speeds the reverse is true. It should be pointed out here that gear ratios should be such that relatively high cranking speeds are necessary. These gear ratios should be based on the probable velocity of aircraft to be encountered in order to remain within the range of optimum rotating speed.

Of the other types of controls mentioned, there does not seem to be much, if any, conclusive literature regarding their relative merits. However, certain principles regarding their proper application can be stated. As in the case with handwheel controls, the movement of joy stick and knob controls should be in the expected or preferred direction, that is, a clockwise movement of the knob control should produce a clockwise movement of the controlled element, and a deflection of a joy stick to the right should cause a rightward movement of the controlled element.

No conclusive evidence has been uncovered that proves beyond any doubt the superiority of one type of control over another. However, when an operator is asked to track a target moving in two dimensions, a single, two-dimensional control seems to be far superior to two one-dimensional controls.

When utilizing a joy-stick type of control, it may be wise to remember that, while gross adjustive movements may be made very rapidly, final precise adjustive movements are very awkward. For this reason it has been recommended by Woodson (46) that control ratios for each type of movement be adjustable by mechanical or

electronic means. Also, of some considerable importance in the use of joy sticks is the method of mounting. This is especially true for the smaller type of controls which are operated by finger or wrist movements. In this case, a limb support in the form of a rest under the forearm provides for steadiness in tracking and consequently greater accuracy in making adjustive movements.

In a recent investigation, it was recommended that due to the relative importance of comfort of the operator in the tracking task, design engineers should avoid the use of long joy stick controls (19). Furthermore, joy stick length was set at 18 inches, except in situations where operator's workspace would necessitate a reduction in size.

As a final statement regarding the selection of the proper type of control, it must be pointed out that there is no definite answer to this problem. Ely, Thomson, and Orlansky (8) have stated that for tracking on a PPI radar scope, a joy stick is better, but when visually tracking an aircraft in an antiaircraft system, two hand cranks (handwheels) are better because the maximum control ratio for a joy stick would be too low.

So far we have been primarily concerned with factors inherent in the tracking system and their effect on tracking accuracy. While these are of prime importance there are certain other elements that must be considered if we are to develop a system of maximum precision. The first of these involves what has come to be called the "principle of least effort." In keeping with this principle it has been recommended in many studies that the operation of controls be assigned to the lowest classification of body movements. These body movements are ranked according to difficulty from least to most:

a. Finger movements

b. Wrist movements

c. Forearm movements

d. Shoulder movements

It is not meant to imply that controls should be used with sheer simplicity of movement as the sole criterion for selection; but on the other hand, a control requiring a higher classification of movement should not be used when one of lower classification yields the same results.

Display Systems

In considering visual displays, first let us look at the radar scope as a component part of the tracking system. The three most common types in use are briefly defined below.

a. A-Scan or A-Scope -- In this scope, horizontal dimension is a time sweep since radar target distances are measured only by the time consumed by a pulse's travel to the target and back. They can be displayed as distances along a calibrated base line. Usually this is made to read from left to right, the left side of the scope representing pulse source and the right side the limit of the range being scanned.

b. B-Scan -- The vertical dimension measures sweep time or range (distance from source). The horizontal dimension represents the successive angular orientations of the rotating antenna, and therefore indicates the relative bearing of the target.

c. PPI-Scan -- The Plan Position Indicator presents a circular (polar coordinate) map with the center the position of the radar antenna. Radial distance is range and angular orientation is bearing.

The major factor to be considered in the design of display systems is the determination of the task requirements placed on the operator using the equipment. For the purpose of this report, the task with which we are initially concerned is one of acquisition, and, subsequently, one of following the acquired target. It is obvious then that both speed and accuracy in tracking are primary factors.

One of the essential characteristics contributing to the speed of acquisition is scope size. If an operator is required to scan a scope during periods of no tracking, then the scope size should be such that he is able to cover the complete scope in a short period of time at maximum efficiency. It has been shown that scope sizes of five or seven inches are just as efficient if not more so than scopes of larger size. It is only when the task to be performed requires direct plotting or simultaneous viewing by a number of persons that a scope of large size is likely or more desirable. One other factor favoring a scope of small size in antiaircraft tracking systems is the limited space available in the operator's compartment.

It has been previously mentioned that angular orientation on the scope face represents bearing. On many scopes, grid markings are utilized for bearing reference. These lines are radial and in most large scopes occur every ten degrees. Used in conjunction with these lines is a numbered bearing dial outside of the display to facilitate more accurate bearing estimation. For maximum accuracy, it has been suggested by Woodson (46) that a solid line placed at intervals each 30° and dotted lines for each 10° be used as bearing markers. Most small displays utilize a bearing cursor as a means of determining azimuth. This cursor is a thin radial line which is brought into position to bisect the blip and extends out to the

bearing marker. In much of the equipment in use today, the bearing cursor is electronic and appears on the surface of the PPI as a stationary sweepline. Most of the errors that might be due to parallax are avoided because the cursor is in the same plane as the blip.

One question that undoubtedly arises in the design of tracking systems is: If the operator's workspace is illuminated, will this illumination be detrimental to his performance? Along this line experimenters have varied ambient illumination from almost zero to several foot candles. It has been concluded by the majority of these investigators that light moderately diffused is not detrimental to visibility on a PPI if kept at or below the level of screen brightness. If the screen should be hooded or shielded, ambient illumination may exceed the screen illumination slightly. It was recommended by Smith and Boyes (38) that ambient illumination having no detrimental effect on radar scope vision is on the order of 0.1 foot candle for the unshielded screen. Scope hoods are recommended for a single operator when ambient illumination cannot be adequately controlled.

A cross polarization filter technique has been used and has proved to be quite adequate. This technique uses a polarized light source and a polaroid filter over the scope face. With this technique, it is not necessary to work in completely darkened rooms, thus allowing sufficient illumination for other personnel in the compartment to carry out other tasks.

In some antiaircraft systems, optics of various magnifying powers are utilized as displays. The effects of magnification illustrate the necessity for affecting compromises in the design of equipment for optimal human operation. In an aided tracking experiment (10), substitution of a six-power monocular telescope for an open viewing tube reduced the average tracking error from 0.82 mil to 0.30 mil, and a further increase to 20 power resulted in a further reduction of error to 0.26 mil. The introduction of magnification in the tracking situation makes errors perceptible sooner and favors more accurate observation of the rates of motion, seemingly permitting prompter correction. It is important to point out here, however, that gains attributable to magnification are offset to some extent by the loss of accuracy due to diminution of field of view as well as to an increase in apparent velocities and accelerations due to target or mount vibration. The constricted field of view makes it difficult to get on and stay on target. The increase in apparent motion as well as the reduced field make slewing more necessary as well as more difficult.

The atmosphere between target and observer also places a limit on the ultimate precision that can be achieved in telescope viewing. Certain atmospheric conditions such as heat shimmer or fog may cause distortion in vision. These distortions increase in a direct proportion to increase in magnification. In order that the effects of target distortion may be kept at a minimum, the power of the optic used in any tracking system should not exceed the limits required by the task. The selected optic should also be the result of studies considering the necessary speed of tracking, mount stability, regularity of the course to be tracked, accuracy required, as well as the size of the object or objects to be tracked.

In a recent study by Kurke and McCain (28), it was recommended that a 2 1/2- or 3-power monocular should be used to detect aerial targets at a range of 10,000 yds. It was assumed that the smallest magnification which would provide detection at the maximum range required by a given system would be optimum magnification for the following reasons:

a. Distortion due to shimmer and vibration are less pronounced.

b. With standard optics, the lower the magnification the larger the field of view for acquisition.

c. Larger exit pupils are obtainable with low power optics for a given objective lens. Large objective lenses are important under conditions of low illumination such as dawn and dusk.

Compensatory vs. Pursuit Tracking

There are two distinct types of tracking tasks. They are compensatory and pursuit tracking. The question naturally arises as to the difference between the two and which is most accurate. In compensatory tracking the operator has to manipulate the controls so as to keep the target aligned with a stationary reference marker. The target movements which the operator views in the display system stem from the movements of the control and the movements of the external target that is being tracked. In pursuit tracking the target in the display moves as a result of the movements in the real external target. The target follower is the element moved by the control. The operator sees both the target movements and the movement of the follower as two separate elements of the display with only the latter under his control. Pursuit tracking is usually used in antiaircraft and other fire control systems.

In a series of experiments conducted by Chernikoff, Birmingham, and Taylor (4, 5) comparing compensatory and pursuit tracking, it was hypothesized that in a one-dimensional tracking task and under conditions of no-aiding, pursuit tracking would be superior to compensatory tracking. However, under conditions of aiding, no difference in accuracy would be found between the two modes. In the undimensional tracking task subjects were required to track a course varying in speed. It was found that in the slowest course, there was no significant difference in error scores between the two modes of tracking. With the other courses containing frequencies 3, 6, and 9 times that of the slowest course, pursuit tracking was significantly more accurate than compensatory tracking. The absolute difference in favor of pursuit tracking increased as the course level difficulty increased.

When the tracking tasks were performed under conditions of no-aiding, pursuit tracking resulted in less errors than did compensatory. Under conditions of aiding, the amount of error in pursuit tracking was increased while the error in the compensatory mode was decreased. Under aided conditions, no significant difference was found between the two modes, but pursuit-unaided was significantly better than any other condition investigated.

It was concluded by Chernikoff, Birmingham, and Taylor that the clear advantage of pursuit tracking over compensatory tracking is brought about by the separate display of target course input, control system output, and error. The findings listed here do not mean, however, that in any tracking situation the pursuit mode will prove most satisfactory. The selection of the proper mode should be a result of the appraisal of the task to be performed, for there are many instances when compensatory tracking should be employed.

Auditory vs. Visual Displays

The possible utilization of auditory displays in the tracking system has been recognized as being quite feasible by numerous investigators. This utilization is demanded by the need to lessen extreme visual burden on operators of present complex visual systems. At the present time though, this type of display is in the experimental stage. The probability does exist, however, that in some tracking situations the visual display will be replaced by the auditory type.

It is the belief of most investigators that visual tracking is superior to auditory tracking. While this statement might be true, we must not lose sight of the fact that this may be a result of training rather than any great difference between eye-hand coordination and ear-hand coordination.

Using auditory signals to represent the tracker's position in relation to target, Humphrey and Thompson (22, 23, 24, 25) ran a series of studies designed to compare auditory and visual tracking. In the initial study the investigators found auditory signals could be used to present information in terms of spatial location. In subsequent experiments, using continuous and discontinuous signals over simple and complex courses, the investigators compared visual and auditory tracking. As a result of these experiments, it was revealed that in situations requiring a high degree of accuracy, visual displays are superior to auditory presentations.

SUMMARY

This report covers some of the design problems in antiaircraft tracking systems. The primary types of tracking and tracking systems are briefly discussed. Attention is focused on the types of controls and their arrangement, physical forces inherent in or added to the control systems, and the dimensions of controls. The types of displays, electronic and optical, are cited and briefly discussed in regard to size, power, and other aspects. No conclusions have been drawn as to what system or component is best at any specific time or under any particular set of conditions; however, the general advantages and disadvantages of each of these components are cited.

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